Chapter 7
Solar Thermal Power Generation and Industrial Process Heat

In time, manufacturing will to a great extent follow the sun

C.G. Abbot (1928)

7.1 Overview

High temperature heat production requires a concentrator, an absorber and a heat transfer fluid, with the addition of an engine if electricity is to be generated. Reflector materials need to retain high specular reflectance under often harsh conditions. Specialised high-temperature selective multiple cermet layer coatings prepared by physical vapour deposition are necessary for operating temperatures above 400 °C (Kennedy and Price 2006). Selective coatings for medium-temperature applications such as metal-dielectric cermet composites of metal particles in a ceramic matrix are not stable at high operating temperatures.

Energy from concentrating insolation when converted to a high temperature fluid can either drive an engine for electricity generation or be used directly for industrial or thermochemical processes. For both applications, heat storage may be both feasible and economically viable. There are a range of combinations shown in Fig. 7.1.

Solar heat can also be converted to electricity using Seebeck thermoelectric effect devices operating under high solar energy concentration. Solar thermoelectric electricity generation has been achieved with an efficiency of 4.6 % for an air-mass 1.5 solar spectrum at 1,000 Wm^{-2} (Kraemer et al. 2011).

Solar thermal power generation technology generally refers to a power generation system that involves collecting solar radiation through concentrated collectors to an absorber surface which will heat a carrier fluid to a high temperature. Solar tracking mode are shown in Fig. 7.2, heliostat mirrors in central receiver systems and parabolic dish systems fully track the Sun. Parabolic trough and linear Fresnel lens systems generally employ E-W polar tracking mode.

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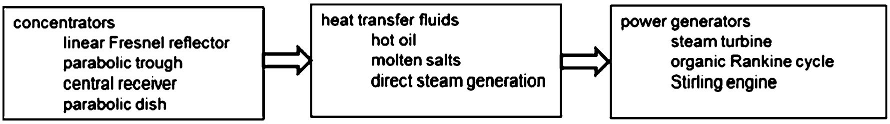
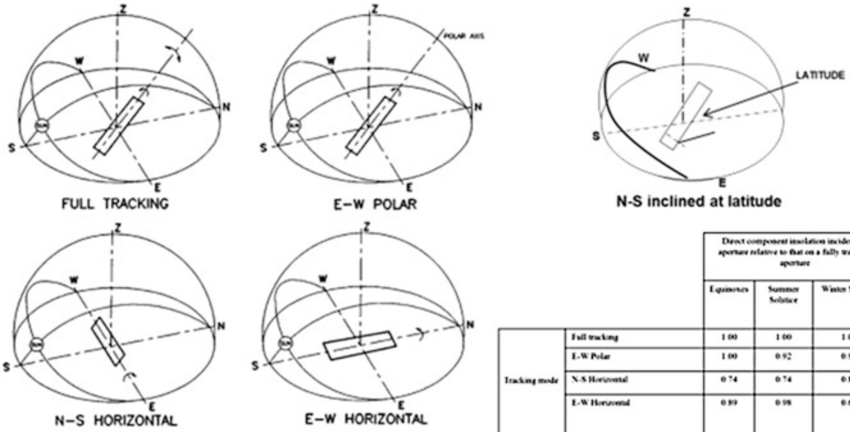


Fig. 7.1 Generic component options in solar thermal power generation systems



		Direct component insolation incident on aperture relative to that on a fully tracking aperture		
		Equinoxes	Summer Solstice	Winter Solstice
Tracking mode	Full tracking	1.00	1.00	1.00
	E-W Polar	1.00	0.92	0.92
	N-S Horizontal	0.74	0.74	0.86
	E-W Horizontal	0.89	0.98	0.61
	N-S Inclined at latitude	0.87	0.68	0.70

Fig. 7.2 Solar tracking modes

Thermochemical hydrogen production process is based on the use of concentrated solar radiation as the energy source of high-temperature process heat for driving an endothermic chemical transformation (Seinfeld 2005; Rodat et al. 2009). Large-scale concentration of solar energy is mainly based on three optical configurations using parabolic reflectors, namely: trough, tower, and dish systems. At higher concentration ratios lower heat losses from smaller area absorbers ensue giving higher temperatures at the receiver.

Through a piping and boiling system the hot fluid will be able to generate steam to power a turbine. Using concrete to store sensible heat for parabolic trough power plants with synthetic oil as the heat transfer fluid has been investigated as has a graphite-based, high-temperature sensible heat storage system. Solar thermochemical processes convert solar energy into chemical energy, with the absorbed, concentrated, solar radiation driving an endothermic chemical reaction. Concentrated solar radiation is used as the energy source for high temperature process heat to drive chemical reactions for the production of storable fuels. Solar heat can also be used to drive a reversible reaction in a solar chemical reactor; after transporting the latter to where the energy is to be used, an exothermic reverse reaction yields the stored energy.

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The first patent for a solar powered engine was granted to Mouchout (1869, 1879) for glass-enclosed iron sphere through which concentrated insolation was transmitted from a two-axis sun tracking mirror to heat water to operate a steam engine. Adams (1878) developed an improved mirror array. From at least 1868 until 1889, Ericsson (1868, 1884; Church 1907) developed a solar-powered steam engine that was the first to include a parabolic trough collector. Tellier (1889) designed of the first solar engine powered by a flat plate collector using pressurised Ammonia working fluid to drive a water pump. In marked contrast, a 10 m diameter conical dish reflector comprised 1,788 individual mirrors concentrated solar energy onto an absorber to generate steam that was transferred to an engine that drive an irrigation water pump (Eneas 1901); the structure supporting the large weight of the reflector proved unable to cope successfully with strong winds and hailstorms. Shuman and Boys (1917) used sun-tracking line-axis parabolic troughs to focus insolation on a tube surrounded by a glass envelope to drive a steam engine (Shuman 1911). In 1912 it was used to power an irrigation plant near Cairo, Egypt. In a parabolic trough solar power plant use a large field of parabolic trough track the sun during the day to concentrate insolation onto a receiver tube located at the focus of the parabolic mirrors. A heat transfer fluid passes through the receiver and is heated to temperatures required to generate steam that in most systems drives a conventional Rankine cycle steam power plant.

7.2 Parabolic Trough Systems

7.2.1 Overview

Parabolic trough reflectors concentrate sunlight onto receiver tubes in which a transfer fluid is circulated as shown in Fig. 7.3. Heated to approximately 400 °C, this fluid, usually a specialist oil, is then pumped through heat exchangers to produce superheated steam. The steam is converted to electrical energy in steam turbine generator, the latter can be integrated into a combined steam and gas turbine cycle.

Fixed-Mirror Tracking absorber systems employ segmented or parabolic reflector as shown in Fig. 7.4. Concentration ratios of up to 50 can be obtained with an average optical efficiency of about 60 % (Pujol et al. 2011).

Fig. 7.3 Parabolic trough concentrators

Fig. 7.4 Tracking-absorber fixed-reflector system (Pujol et al. 2011)

7.3 Fresnel Mirror System

A linear concentrating Fresnel solar concentrator is an planar array of linear mirror strips that reflect sunlight onto a stationary thermal receiver as shown in Fig. 7.5. The operation temperature range is 100–400 °C.

In a linear Fresnel reflector, a single-axis tracking of an array of mirror strips focuses insolation onto a linear receiver. Linear Fresnel reflector systems have relatively low initial cost as inexpensive planar mirrors are driven by a simple tracking system and the area required is used efficiently by the mirror strips for one absorber being interspaced with those for the adjacent absorber. The fixed absorber tube obviates the need for flexible high pressure joints or thermal expansion bellows. As the reflector strips are ground-mounted, wind loads on the reflector strips are low; the reflector width per absorber tube can therefore be three times that of a parabolic trough. When used for direct steam generation, no heat exchanger is

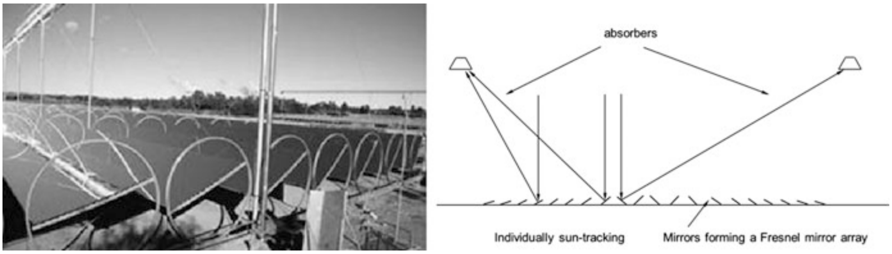

Fig. 7.5 A compact linear Fresnel reflector system

required. A disadvantage of linear Fresnel systems is a reduction in the efficiency compared to parabolic troughs, which has to be compensated for by a lower investment cost in the solar field. These cost reductions can come from economies of scale and design optimisation of the collector and there are also potential savings offered by lower operation and maintenance costs.

7.4 Heliostat Field Central Receiver Systems

Solar power tower systems consist of a field of heliostat sun-tracking mirrors that reflect direct insolation to a receiver located at the top of a tall tower as shown in Fig. 7.6. A molten salt heat-transfer fluid, heated in the receiver is used to generate the steam required for a steam turbine-generator to produce electricity. Both parabolic trough and solar power tower systems have inherent economy of scale as they are coupled with turbine generators whose minimum economic capacity is usually over 50 MW.

Each heliostat consists of a tracking unit with drive motors, controls as well as the reflector. Being dual-axis tracking, heliostats are adjusted constantly. A circular or semi-circular array as shown in Fig. 7.7 of large individually-tracking heliostat mirrors concentrate sunlight onto the central receiver.

Water, steam, molten salts, liquid sodium and air are employed as intermediate heat transfer fluids. With concentration ratios exceeding 500, power towers deliver solar heat at temperatures of over 500 °C and over 1,000 °C for steam cycles and gas turbines respectively. Modern central receiver technology was demonstrated during the 1980s with the "Solar 1" and "Solar 2" facilities in California. "PS-10", an 11 MW central receiver system near Seville, Spain, commenced operation in 2007. The heliostat field of "Solar Tres", a 17 MW steam-generating central receiver system is three times the size of Solar Two comprising 2,493 96 m^2 glass-metal heliostats with 16 h of heat storage provided by a 600 MWh 6,250 tonne molten nitrate salt thermal energy store.

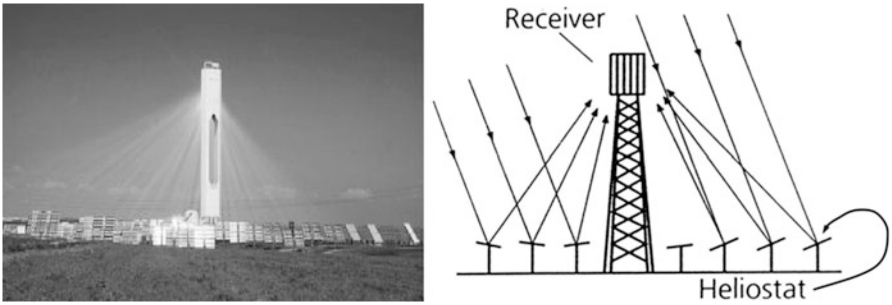

Fig. 7.6 11MW PS10 heliostat and central receiver system near Seville, Spain

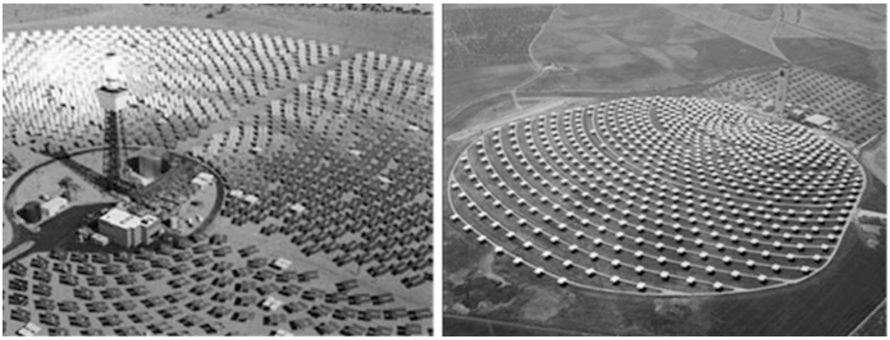

Fig. 7.7 Large scale heliostat arrays

7.5 Parabolic Dish Systems

Parabolic dishes concentrate insolation onto an absorber as shown in Fig. 7.8. The latter can be a Stirling engine where air is heated and transferred from the hot cylinder to the cold cylinder of the engine; the working fluid movement is used to generate electricity.

As parabolic dishes are always aligned to the solar position, they operate at their highest optical efficiency. This optical efficiency is considerably higher than that of trough, linear Fresnel receiver or central receivers where cosine losses ensue.

Solar Parabolic dishes are usually composed of mirror facets that focus solar energy onto a receiver as shown in Fig. 7.9. A heated working fluid such as hydrogen drives a turbine or, more usually, a Stirling engine.

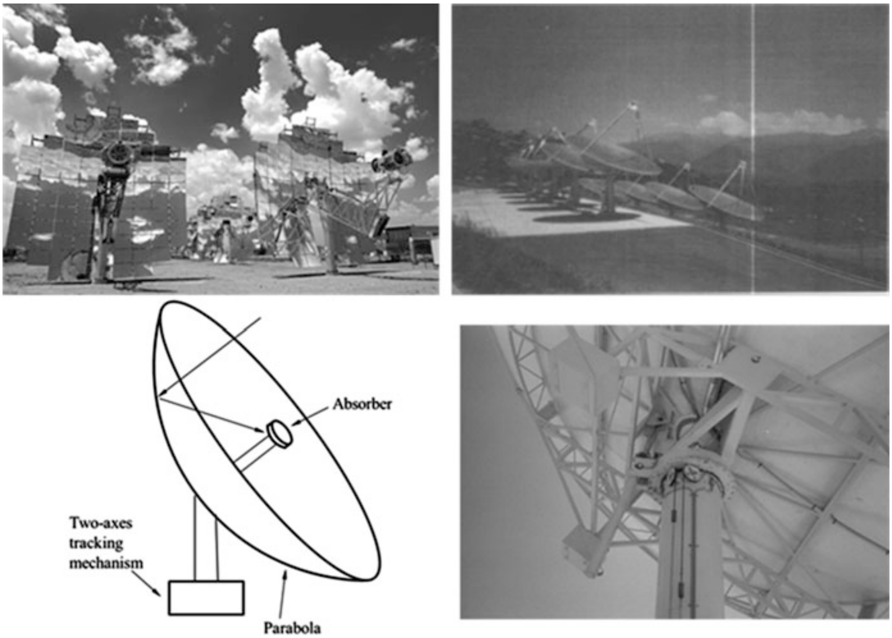

Fig. 7.8 Parabolic dish reflectors, schematic diagram and photographs

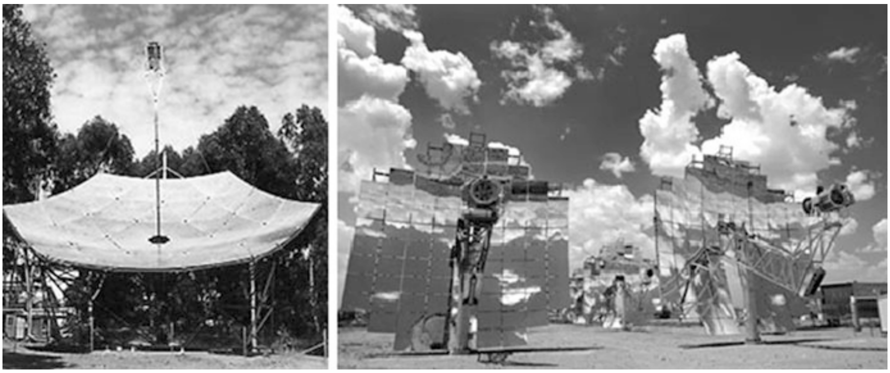

Fig. 7.9 Parabolic dish reflectors fabricated from mirror segments

7.6 Characteristics of Concentrating Solar Thermal Electricity Generating Systems

Solar thermal power generation can be operated:

- To generate solely when direct insolation is sufficient
- As a "solar-assist" to provide steam to an existing generating plant as it integrate well with conventional thermodynamic cycles and power generation equipment

Table 7.1 Thermal photovoltaic and thermoelectric conversion of solar heat to electricity

	Parabolic trough	Central receiver	Parabolic dish
Typical power (MW)	30–320	10–200	5–25
Operating temperature (°C)	390	560	750
Annual capacity factor (%)	23–50	20–77	25
Peak efficiency (%)	20	23	29
Net annual efficiency (%)	11–16	7–20	12–25

- As dispatchable power when integrated with thermal storage and/or gas co-firing giving good matching between insolation and where electrical demand is driven by summer air conditioning.

Economic viability is likely to continue to improve with;

- Increasing plant sizes to reduce operating costs through economies of scale as both collectors and systems are fabricated using established manufacturing process with mostly readily available materials
- Development of economically viable thermal storage
- Siting solar thermal electricity generation near gas sources or pipelines to utilise gas as a co-firing fuel (Table 7.1).

Heat engines are employed in all current practical systems for the conversion of solar energy to electricity. Two other approaches are

- Thermophotovoltaics; solar photons heat an intermediate solar selecture absorber that re-emits photons whose energy matches the band-gap of a thermophotovoltaic (TPV) cell. TPV cells have a theoretical maximum efficiency of 85.4 %, similar to infinite multijunction cells without the latter's complexity in fabrication (Morti and Luque 2003). The key barrier to implementation has been the absence of highly efficient selective surfaces structured at 10 nm scales (Bitnar et al. 2002; Fleming et al. 2002). With such materials device efficiency should approach 30 %.
- Thermoelectric, a voltage is generated by a temperature difference across a material. The underlying "Seebeck effect" is however small for even application-specific materials (Goldsmid 1960), though research on novel nanomaterials (Chen 2001; Chiritescu et al. 2007).

7.7 Non-convecting Solar Panels

In a non-convecting solar pond, part of the incident insolation is absorbed and converted to heat, which is stored in lower regions of the pond. Solar ponds are both solar energy collectors and heat stores.

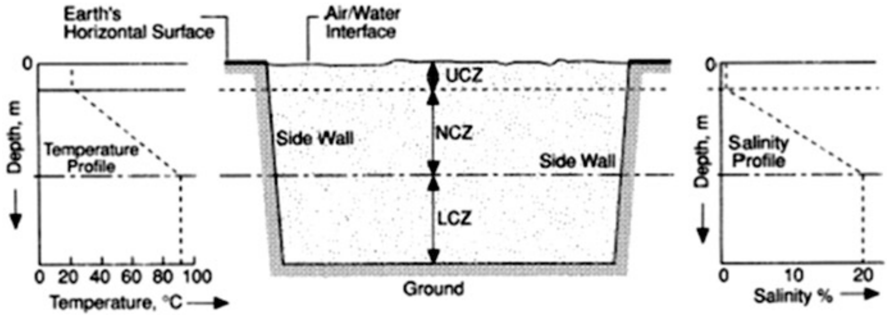

Fig. 7.10 Zones in a non-convecting solar pond

An operating salt-gradient non-convecting solar pond consists of three zones as shown in Fig. 7.10:-

- The upper-convecting zone (UCZ), of almost constant low salinity at close to ambient temperature. The UCZ, typically 0.3 m thick, is the result of evaporation; wind-induced mixing and surface flushing. It is kept as thin as possible by the use of wave suppressing surface meshes and placing wind-breaks near the pond.
- The non-convecting zone (NCZ), in which both salinity and temperature increase with depth. The vertical salt gradient in the NCZ inhibits convection and thus provides the thermal insulation. The temperature gradient is formed due to the absorption of insolation at the pond base.
- The lower-convecting zone (LCZ), of almost constant, relatively high salinity (typically 20 % by weight) salinity at a high temperature. Heat is stored in the LCZ which is sized to supply energy continuously throughout the year. As the depth increases, the thermal capacity increases and annual variations of temperature decreases. However, large depths increase the initial capital outlay and require longer start-up times.

There are Salt gradient lakes that naturally exhibit an increase in temperature with depth. For example Medve Lake in Transylvania (Nielsen 1975) contained a nearly- saturated NaCl solution at a few metres depth, with almost fresh water at its surface. The maximum temperature exceeded 60 °C at a depth of 1.32 m at the end of Summer; the minimum temperature being around 26° during the early Spring. A similar lake near Orville in north-central Washington, USA (Anderson 1958) whose salt is principally magnesium sulphate, exhibited a temperature of around 50 °C in July 1955 at a depth of 2 m, whilst the surface temperature was less than 26 °C. Lake Vanda in the Antarctic is another natural example of the trapping and storing of solar energy as a result of a salt-water density gradient (Wilson and Wellman 1962). The bottom of this lake (−67 m depth) is maintained at −25° despite a mean annual air temperature of about −20 °C. Other natural solar lakes, include the Los Reques lake, Venezuala (Huder and Sonnefeld 1974); Lake Magege in western Uganda (Melack and Kilham 1972); Castle Lake in California, USA

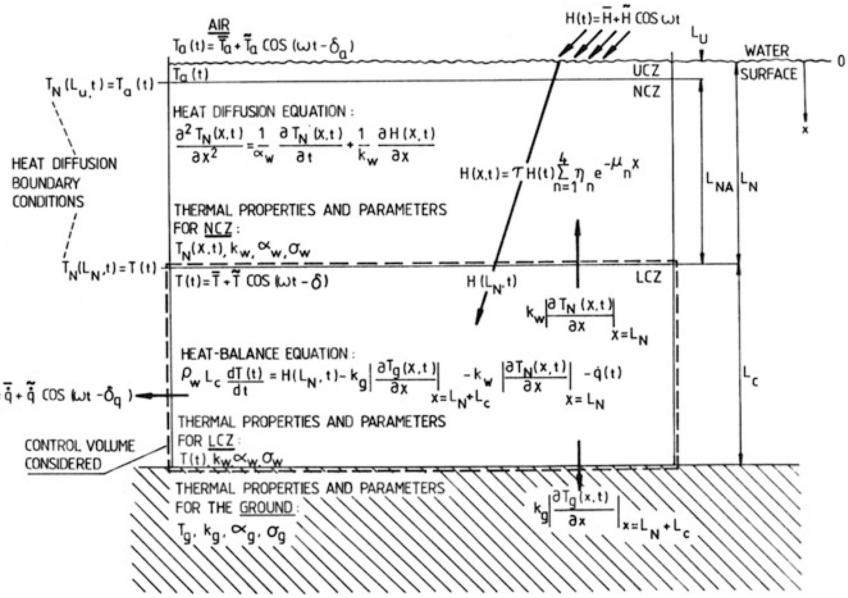

Fig. 7.11 Heat transfer processes in a non-convecting solar pond

(Bachmann and Goldman 1965) and a lake on the shores of the Red Sea, on the east coast of Sinai Peninsula where the temperature rose from 16 °C at its surface to 40° at 1.5 m depth (Por 1968).

The first theoretical analysis of thermophysical behaviours in solar ponds (Weinberger 1964) was a one-dimensional non-convecting model, was employed to predict annual variations of pond temperatures. The key aspects of such analyses are shown in Fig. 7.11. The large thermal capacity of a solar pond dampens its response to diurnal variations in insolation, typically the average temperature of an LCZ varies by less than 1 °C over 24 h (Kooi 1979). However, large annual changes in the daily-average LCZ temperature may occur. Thus an annual sinusoidal variation is an appropriate representation of insolation, (Rabl and Neilsen 1975). Following the approach of Abdel-Salam et al. (1986) varied the heat extraction rate occurs over an annual cycle as a sinusoidal temporal function of phase-lag relative to the insolation. The mean temperature of the UCZ is usually assumed to be that of the ambient air. The LCZ is usually assumed to be homogenous with a uniform salt concentration and fully convective so that its temperature will thus be a function solely of time. The energy balances for a non-convecting solar pond is presumed to have passed through an initial start-up phase and to be operating in a steady-state manner (Abdel-Salam et al. 1986).

From the late 1950s to the late 1980s (with a break in the late 1960/early 1970s) experimental solar ponds have been operating in Israel (Tabor 1981; Tabor and Matz 1964). A salt-gradient solar pond of 2.5 m depth and 200 m^2 effective collector area was constructed in August 1975, at the Ohio State University,

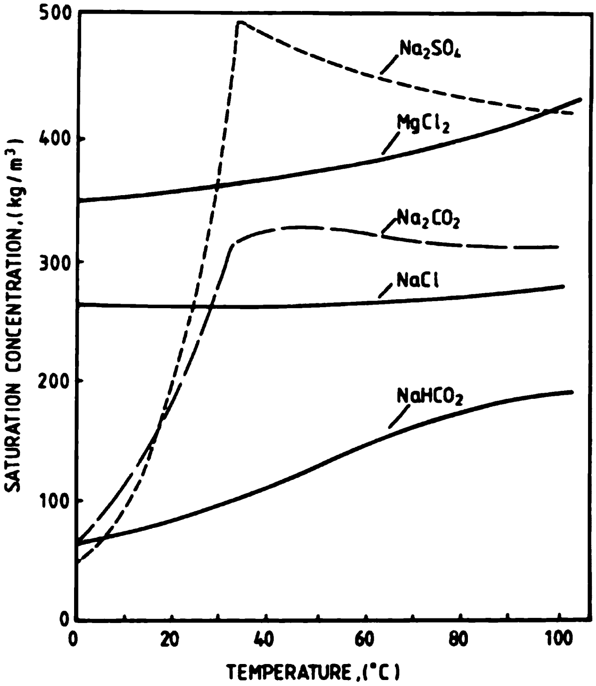

Fig. 7.12 Solarbility of salts in water

USA, for space heating (Nielsen 1976). A solar pond constructed in 1978 has heated an outdoor swimming pool in summer and a recreation building during part of the winter, In Miamisburg, Ohio, USA (Bryant et al. 1979).

The application of solar ponds for electric-power production usually employs an organic vapour Rankine Cycle engine to convert solar-pond heat to mechanical work, and then into electricity. However, to obtain a low cost per generated Watt, solar ponds of several kilometers are required.

Many techniques have been considered in order to suppress natural convection in order to create a solar pond. The most common method used is salt-stratification. Salinity increases with depth in the NCZ until the LCZ is reached: the highest salt concentration occurs uniformly throughout this region. Here the solar radiation will heat the highly saline water, but because of its high relative density (due to its salt content), this hot salt-water will not rise into the lower salinity layers. Thus the heat is stored, yet inhibited from being transferred by convection. Chemically-stable salts, as well as any natural brine can be used to establish a salt-stratified solar pond. A selected salt must be safe to handle; non-toxic; cheap and readily available; not reduce significantly the insolation transmission characteristics of water; and solubility should be temperature dependent. The variation of solubility with temperature for candidate salts is shown in Fig. 7.12.

Sodium and magnesium chlorides though satisfying most criteria (especially sodium chloride in terms of cost) have, solubilities that are modestly temperature dependent. However salts which possess more appropriate variations of solubility

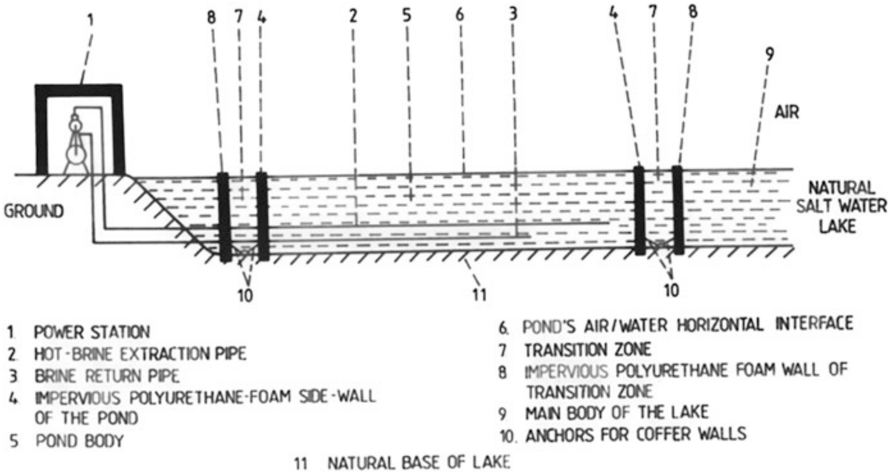

Fig. 7.13 Coffered solar pond

with temperature, do not meet the remaining constraints. Thus sodium chloride remains the most popularly used salt.

Some of the early designs of saline non-convecting solar ponds employed membranes (Rabl and Neilsen 1975) to provide boundaries between the pond zones and prevent upward salt diffusion. However, membranes present major fabrication and maintenance problems, especially for large ponds.

The “Floating” Solar Pond was first suggested in 1976 (Assaf 1976). The Floating Solar Pond is a conventional solar pond “floating” on a large saline lake and enclosed by thermally-insulating walls (Tabor 1981). In the enclosure, the uppermost few metres of the water have an imposed salt-concentration gradient, with an inverse gradient in the lower depths. Two designs have been proposed for floating solar ponds (Crevier and Moshref 1981) which depend on the conventional salt gradients above convecting layers. Intermixing was to be prevented by a horizontal flexible membrane, which were to be held in place by a combination of buoys and weights. Although the Floating Solar Pond avoids the land costs and the need for excavation, the uncertain behaviour of the boundary layer between the LCZ and the lake water beneath it and the need for the use of membranes are major disadvantages. An alternative approach to utilizing existing lakes is the coffered solar pond (Abdel Salam et al. 1986) shown in Fig. 7.13.

In a “saturated solar pond”, water at all levels is saturated with salt, and upward salt diffusion is avoided. The pond The chosen salt should possess a solubility, which increases significantly with rising temperatures; the salt gradient would be self-maintained depending upon the local temperature gradient. A saturated solar pond requires far more salt than a conventional non-convecting salt-gradient solar pond. The absence of a salt which has the required properties has prevented the practical construction of a saturated solar pond (Satish and Gurmukh 1980), however aluminium sulphate dodecahydrate has a very temperature dependent solubility and has been proposed (Vitner et al. 1984).

For power production in the multi MW, a solar pond of several-square kilometres surface area is needed. However, this is not feasible economically as excavation and preparation work account for more than 40 % of the total capital cost of the power-generating station (Tabor 1981). So it would appear logical to employ a natural lake, and convert a shallow portion of it into a solar pond. The "coffered solar pond" has been proposed (Abdel-Salam et al. 1986). This is formed by physically isolating a section of a natural lake using walls of thermally-insulating materials.

In a Viscosity-Stabilised Solar Pond, organic thickeners are added to the pond layers thereby creating a static stabilised zone. By increasing the proportion of thickeners, the water becomes more viscous until natural convection is suppressed entirely. Promising prospective thickeners include cellulose methyl ethers, sodium caboxy methyl cellulose and a commercial carboxy vinyl (acrylic) polymer (Shaffer 1978). The problems with thickeners include maintaining the stability of the static zone under the effect of shear stresses and decomposition of the thickeners with time and at temperature above 55 °C.

In a Gel-Stabilised Solar Pond, the stratified non-convecting zone of the traditional salt-gradient solar pond is replaced by a transparent layer of highly viscous or near-solid polymer-gel (Wilkins et al. 1982). As such gels have low thermal conductivity, and are almost solid, they will convect insignificantly. Upward heat transfer will thus be predominantly conductive. Gel ponds overcome the two main problems of conventional solar ponds, maintaining stratification and the inhibition of wind mixing.

The site for a solar pond should be near a cheap source of salt, an adequate source of water, incur low land costs, and experience an all-year solar exposure. The underlying earth structure should be homogeneous and free of stresses and fissures. If not, then increases in temperature may cause differential thermal expansions which could result in earth movements (Tabor 1980). The pond must not pollute aquifiers nor lose heat via underground water streams passing through an aquifier. Any continuous drain of heat will lower the pond's storage capability and effectiveness. Stormy regions should be avoided in order to limit wind surface mixing effect.

Species of fresh-water and salt-water algae grow under the conditions of temperature and salt concentration that exist in a stratified solar pond. Algae growth will inhibit solar transmissivity and insolation (Wittenberg and Harris 1980). Different algae species are introduced by rain water and air-borne dust. To prevent algae formation, copper sulphate has been added at a concentration of about 1.5 mg/l. This has proved to be effective (Poppe and Woomer 1985). The thermal efficiency of a pond depends on the stability of its vertical salt-gradient. The pond will cease to function without the proper maintenance of the stratification. The stability of the salt-gradient is maintained by:

- Controlling the overall salinity difference between the two convecting layers
- Inhibiting internal convection currents if they tend to form in the NCZ; and
- Limiting the growth of the UCZ.

Salt slowly diffuses upwards at an annual average rate of about 20 kgm^{-2} as a result of its concentration gradient. This rate varies and is dependent upon the ambient environment conditions, type of salt and temperature gradient. A combination of surface washing by fresh water and injecting brines of adequate density at the bottom of the pond is usually sufficient to maintain an almost stationary gradient. Several techniques have been developed to achieve this (Nielsen and Rabl 1976; Tabor 1980; Akbarzadeh and MacDonald 1982).

During pond heating, and particularly at higher temperatures, small, unstable, convecting zones may develop within the NCZ. If these zones are left unattended, they will increase in thickness, and this leads to a decrease in the effective thickness of the NCZ. To restore the gradient, brine is injected horizontally from a diffuser placed at the upper boundary of the unstable region. This wave of increased density descends until the lower boundary of the unstable region is reached. The downward velocity of the diffuser and the rate and the density of the brine injected from it are adjusted in such a way that to restore the stability of the gradient (Zangrando 1980). Alternatively external mixed brine of the appropriate concentration may be injected slowly into the unstable region (Nielsen 1979).

Surface flushing is an essential process in maintaining the pond's salt-gradient. Its effect on the UCZ growth is reduced if the velocity of the surface washing water is small. Surface temperature fluctuations will result in heat being transferred upwards through the UCZ by convection, especially at night, and downward by conduction. The thickness of the UCZ varies with the intensity of the incident insolation. In an experimental solar pond at Melbourne University, Australia, the thickness of the UCZ varied between 10 and 15 cm from night time to mid-day (Akbarzadeh et al. 1983).

Evaporation will be caused by insolation and wind-action. The higher the temperature of the UCZ, and the lower the humidity above the pond's surface, the greater will be the evaporation rate. Excessive evaporation results in a downwards growth of the UCZ (Onwubiko 1984). Evaporation can be counter-balanced by surface water-washing, which could compensate for evaporated water as well as reduce the temperature of the pond's surface especially during periods of high insolation. Reducing the wind velocity over the water's surface by using wind breaks will reduce evaporation rates. Evaporation can be the dominant mechanism in surface-layer mixing under light-to-moderate winds. However, under strong winds it becomes of secondary importance. Wind-induced mixing can contribute significantly to the deepening of the UCZ. Winds also induce horizontal currents near the top surface of the pond increasing convection in the UCZ region (Elata and Levien 1966). Wind-mixing has been reduced by floating devices (e.g. plastic pipes, plastic grids and independent rings) and by the use of wind-breaks. UCZ deepening may be suppressed by decreasing the potential energy of the top surface layer of the pond. This may be accomplished by raising the overall salinity of the pond, and then washing this top layer with non-saline water to produce a thin surface sub-layer. More kinetic energy than possessed by surface winds is required to mix this sub-layer with the bulk of the UCZ. Wind energy would thus be dissipated mixing the top layer and little energy would remain to lower the level of the interface between the UCZ and the NCZ (Schladow 1984).

Water is a spectrally selective absorber, only shorter wavelengths reach the bottom of the pond. This has been represented by a sum of four exponential extinction functions, (Rabl and Neilsen 1975) to give an effective absorption coefficient, that is the absorption coefficient divided by the cosine of the angle of refraction. This allows for the increased path length due to refraction of the incident insolation at the water surface.

7.8 Solar Chimney Power Plants

A solar chimney power plant consists of a transparent tubular chimney over 200 m tall rising from a horizontal ground area of over 50,000 m^2 covered with a transparent material (Haaf et al. 1983). At the base of the chimney is located a turbine driven by the natural circulation air flow as shown in Fig. 7.14. In the climate of South Western Algeria such a system can produce between 70 and 43 MW of electricity per month in July/August and December/January respectively (Larbi et al. 2010). Early investigations of solar chimney power plants were undertaken from the 1900s to 1930s (Cabanyes 1903; Günther 1931). Detailed studies by Haaf et al. (1983); Haaf (1984) Schlaich (1995) and Schlaich et al. (2003a, b) have shown that performance is dependent strongly on the incident solar energy but is largely invariant with ambient temperature. Simulation models have been developed to produce optimal designs for particular climates (Larbi et al. 2010; Pasumarthi and Sherif 1998; Bernardes et al. 1999; Maia et al. 2009; Pretorius et al. 2004, 2006a, b). Particular attention has been given to increasing power production and reducing installation cost (Fluri et al. 2009; Chergui et al. 2008).

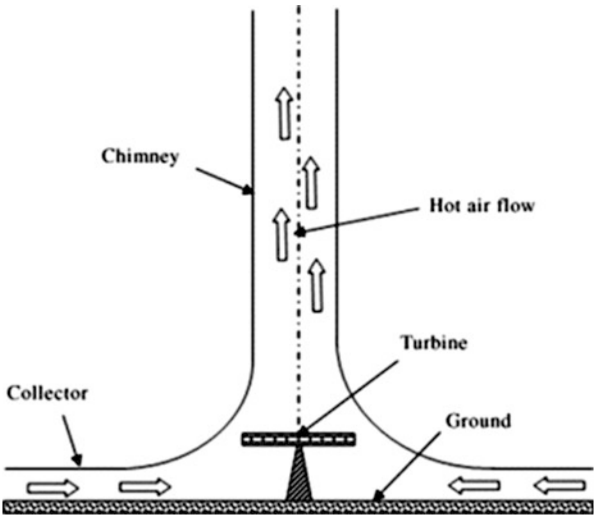

Fig. 7.14 Operation of a solar chimney powerplant

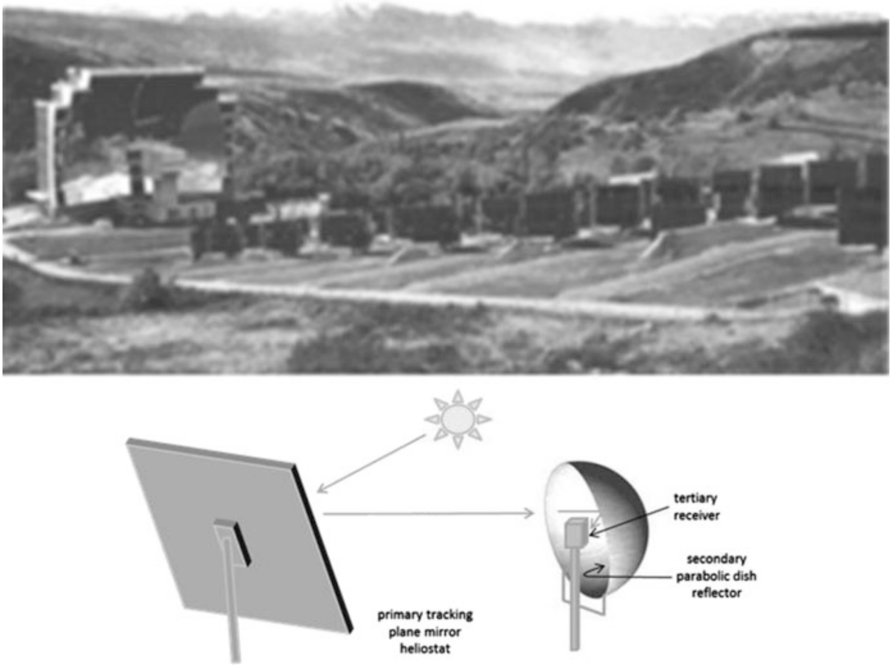

Fig. 7.15 Solar furnace; principle of operation and an installation in Odeillo, France

7.9 Solar Process Heating

7.9.1 Industry

Industrial process heat is an important application of solar energy in medium to high temperature sterilising, pasteurising, drying, hydrolysing, distillation and evaporation, washing and cleaning, and polymerisation (Dincer and Rosen 1998; Schweiger et al. 2000; Kalogirou 2004). However to install solar industrial process heat applications a large initial investment is often needed (Foster et al. 2010).

Industrial process heat at sufficiently low temperatures can be supplied by solar energy. About 40 % of all process heat is in the temperature range from ambient to 180 °C. Process heat requirements below 180 °C can be supplied by flat-plate collectors, solar ponds, evacuated tube collectors or solar concentrators. A comparison of alternative concentrators indicated that the two axes tracking paraboloidal dish is the most promising design for industrial process heat applications in India (Kedare 2005). A design of solar concentrator for medium temperature industrial process heating applications (Chandak and Dubey 2005) that comprised multiple paraboloidal reflector dishes of 12.5 m^2 total aperture area mounted on a structure that rotates parallel to the polar axis tracking the sun delivered heat at 250 °C. Five meter diameter dish concentrators have been used for heat deformation of sheet metal by solar energy (Lytvynenko and Schur 1999). A diagram of a solar furnace is shown in Fig. 7.15.

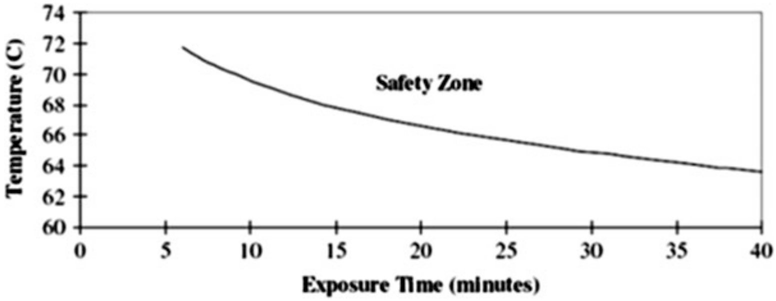

Fig. 7.16 Exposure duration for temperatures between 60 °C and 14 °C required to destroy enteroviruses

7.9.2 Water Treatment Using Solar Energy

Solar energy water treatment systems are a low cost and effective method of reducing microbiological contamination in drinking water (WHO 2007). With no requirement to heat water to boiling, pasteurisation is a promising method for purifying water using solar energy (Duff and Hodgeson 2007). Being unaffected by the turbidity of that is often a feature of many water supplies, gives pasteurisation an advantage over ultraviolet disinfection and filtration; both the latter are negatively influenced by turbidity (Burch and Thomas 1998). Pasteurisation raises, and then maintains, water to an elevated temperature for the duration required to achieve microbiological decontamination. As an example, the duration required to destroy Enteroviruses (Feachem et al. 1983) is shown in Fig. 7.16.

Submicrometer nanoparticles can absorb solar energy across its spectrum. When such nano particles, suspended in water, are exposed to concentrated solar energy a thin layer of steam is formed. This layer both reduces thermal conductance from the nanoparticle to the surrounding water and generates buoyant forces that carries columns of steam bubbles and nanoparticles to the water surface. At the surface the steam is realised and the nanoparticle descends back into the bulk liquid. Eventually the bulk temperature of the water rises until, if the solar energy input insufficient, conventional boiling ensues (Neumann et al. 2013). The phenomena has potential use for solar energy application and in sterilization.

7.9.3 Cooking

A Scheffler concentrator shown in Fig. 7.17 is a paraboloidal reflector with a medium-range concentration ratio used for cooking applications up to 300 °C primarily, to date, in India (Gadhia and Gadhia 2006). In a Scheffler fixed focus solar cooker comprises a primary reflector, a secondary reflector, and clock mechanism powered by clockwork or photovoltaics. The primary reflector produces a converging beam of sunlight aligned with an axis of rotation. The clock mechanism

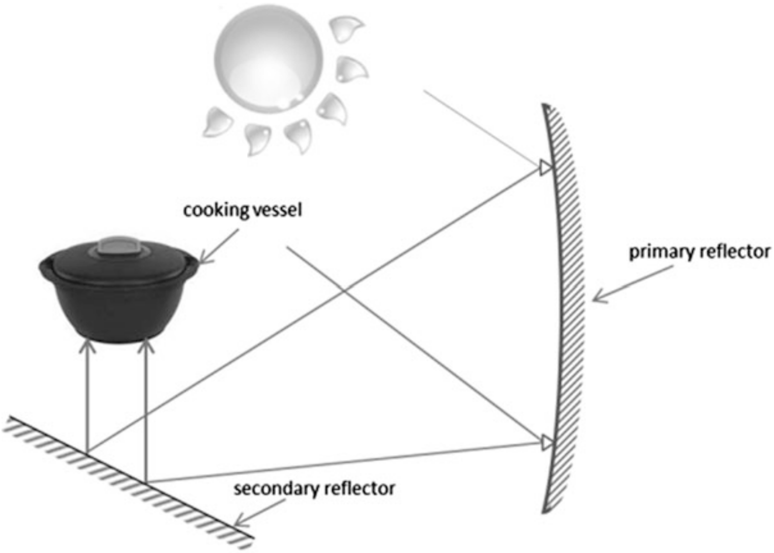

Fig. 7.17 A Scheffler concentrator

Fig. 7.18 Box-type solar cookers

rotates the primary reflector to maintain the alignment of the reflected beam. The fixed secondary reflector reflects the beam from the primary reflector onto a cooking vessel. Each morning, the primary reflector is returned to its starting position and the angle between the axis of rotation and the reflector checked to ensure that seasonal variations in solar azimuth are accommodated. The primary reflector, comprised of flat mirror facets, is a small lateral elliptical section of a much larger paraboloid. Test procedures for such cookers are available (Mullick et al. 1991).

Box type cookers shown in Fig. 7.18 are suitable in appropriate climates for the production of relatively slow-cooked dishes. Rating procedures have been developed for intercomparison of cooking performance (Mullick et al. 1991).

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